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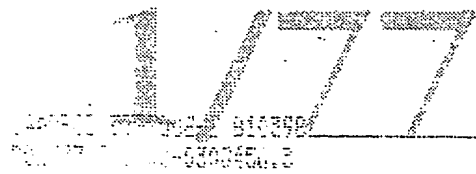
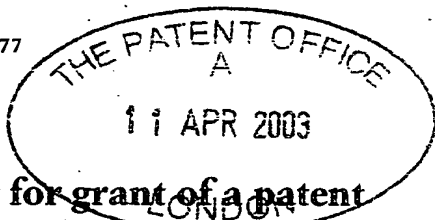
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DAVID MEREDITH, THE BARN, MIDDLE BROAD
DROVE, TYDD ST. GILES,
WISBECH, CAMBS., PE13 5PA.

Patents ADP number (if you know it)

8476296001

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4. Title of the invention

METHOD OF COMPUTING THE PITCH NAMES OF NOTES IN
MIDI-LIKE MUSIC REPRESENTATIONS

5. Name of your agent (if you have one)

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

DAVID MEREDITH,
THE BARN, MIDDLE BROAD DROVE,
TYDD ST. GILES, WISBECH,
CAMBS., PE13 5PA.

Patents ADP number (if you know it)

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Description

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Abstract

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METHOD OF COMPUTING THE PITCH NAMES OF NOTES IN MIDI-LIKE MUSIC REPRESENTATIONS

Field of the invention

This invention relates to the problem of constructing a robust *pitch spelling algorithm*—that is, an algorithm that reliably computes the correct pitch names (e.g., C#4, Bb5 etc.) of the notes in a passage of tonal music, when given only the onset-time, MIDI note number (The MIDI Manufacturers' Association, 1996, p. 10) and possibly the duration of each note in the passage.

There are good practical and scientific reasons for attempting to develop a robust pitch spelling algorithm. First, until such an algorithm is devised, it will be impossible to construct a robust *MIDI-to-notation transcription algorithm*—that is, an algorithm that reliably computes a correctly notated score of a passage when given only a MIDI file of the passage as input. Commercial music notation programs (e.g., Sibelius (www.sibelius.com), Coda Finale (www.codamusic.com) and Nightingale (www.ngale.com)) typically use MIDI-to-notation transcription algorithms to allow the user to generate a notated score from a MIDI file encoding a performance of the passage to be notated. However, the MIDI-to-notation transcription algorithms that are currently used in commercial music notation programs are crude and unreliable. Also, existing audio transcription systems generate not notated scores but MIDI-like representations as output (see, for example, Davy and Godsill, 2003; Plumbley *et al.*, 2002; Walmsley, 2000). So if one wishes to produce a notated score from a digital audio recording, one typically needs a MIDI-to-notation transcription algorithm (incorporating a pitch spelling algorithm) in addition to an audio transcription system.

Knowing the letter-names of the pitch events in a passage is also indispensable in music

information retrieval and musical pattern discovery (Meredith *et al.*, 2002). For example, the occurrence of a motive on a different degree of a scale (e.g., C-D-E-C restated as E-F-G-E) might be perceptually significant even if the corresponding chromatic intervals in the patterns differ. Such matches can be found using fast, exact-matching algorithms if the pitch names of the notes are encoded, but exact-matching algorithms cannot be used to find such matches if the pitches are represented using just MIDI note numbers. If a robust pitch spelling algorithm existed, it could be used to compute the pitch names of the notes in the tens of thousands of MIDI files of works that are freely available online, allowing these files to be searched more effectively by a music information retrieval (MIR) system.

In the vast majority of cases, the correct pitch name for a note in a passage of tonal music can be determined by considering the rôles that the note is perceived to play in the perceived harmonic structure and voice-leading structure of the passage. For example, when played in isolation in an equal-tempered tuning system, the first soprano note in Figure 1a would sound the same as the first soprano note in Figure 1b. However, in Figure 1a, this note is spelt as a G \sharp 4 because it is perceived to function as a leading note in A minor; whereas in Figure 1b, the first soprano note is spelt as an A \flat 4 because it functions as a submediant in C minor. Similarly, the first alto note in Figure 1b would sound the same as the first alto note in Figure 1c in an equal-tempered tuning system. However, in Figure 1b the first alto note is spelt as an F \flat 4 because it functions in this context as a subdominant in C minor; whereas, in Figure 1c, the first alto note functions as a leading note in F \sharp minor so it is spelt as an E \sharp 4.

Nevertheless, it is not always easy to determine the correct pitch name of a note by considering the harmonic structure and voice-leading structure of its context. For example, as Piston (1978, p. 390) observes, the tenor E \flat 4 in the third and fourth bars of Figure 2 should be spelt as a D \sharp 4 if one perceives the harmonic progression here to be $+\text{II}^2 - \text{I}$ as shown. But spelling the soprano E \flat 5 in the fourth bar as D \sharp 5 would result in a strange melodic line.

Such cases where it is difficult to determine the correct pitch name of a note in a tonal work are relatively rare—particularly in Western tonal music of the so-called ‘common practice’ period (roughly the 18th and 19th centuries). In the vast majority of cases, those who study and perform Western tonal music agree about how a note should be spelt in a given tonal context. This poses an interesting problem for cognitive science, namely: what are the cognitive processes involved when a musically trained individual determines the correct pitch name of a note in a passage of tonal music?

A good way of trying to answer this question is to attempt to construct a robust pitch spelling algorithm that operates in a way that is consistent with what is known about the neurology, physiology, psychophysics and psychology of expert music perception and cognition. Such a pitch spelling algorithm could serve the valuable scientific purpose of furthering our understanding of the cognitive processes underlying an interesting intellectual ability exhibited by many individuals who study and perform Western tonal music.

The vast majority of notes in authoritative published editions of scores of common practice tonal works are generally agreed to be spelt correctly by those who understand Western staff notation. Therefore a pitch spelling algorithm or computational model of pitch spelling can be evaluated objectively by running it on tonal works and comparing the pitch names it predicts with those of the corresponding notes in authoritative published editions of scores of the works. However, this can only be done accurately and quickly if one has access to encodings of these authoritative scores in the form of computer files that can be compared automatically with the pitch spelling algorithm’s output.

Related Art

In this section, I compare the performance of three prior pitch spelling algorithms on a single test corpus of works containing 41544 notes and consisting of all 48 pieces in the first book of J. S. Bach’s *Das Wohltemperirte Klavier*. The algorithms compared are those of Cambouropoulos (1996, 1998, 2000, 2001, 2002), Longuet-Higgins (1976, 1987, 1993)

and Temperley (1997, 2001).

When these algorithms were run on the test corpus, Cambouropoulos's algorithm made 2599 mistakes, Longuet-Higgins's algorithm made 265 mistakes and Temperley's algorithm made 122 mistakes.

The test corpus The test corpus used in the comparison consists of representations of the scores of all 24 Preludes and all 24 Fugues in the first book of J. S. Bach's *Das Wohltemperirte Klavier* encoded in what I call *OPND* format.¹ Each *OPND* representation is a set of triples, $\langle t, n, d \rangle$, each triple giving the onset time, t , the pitch name, n and the duration, d of a single note (or sequence of tied notes) in the score.² The onset time and duration of each note are expressed as integer multiples of the largest common divisor of all the notated onset times and note durations in the score. For example, Figure 3b gives the *OPND* representation of the score in Figure 3a. Note that within each pitch name in an element in an *OPND* representation, each flat symbol is represented by an 'F' character and each sharp symbol is represented by an 'S' character (double-sharps are denoted by two 'S' characters, so, for example, $F\sharp 4$ is denoted by "FSS4".)

The test corpus was derived by automatic conversion from Hewlett's (1997) *MuseData* encodings of Bach's *Das Wohltemperirte Klavier*.³ The *MuseData* encodings contained minor errors which were corrected in the *OPND* representations.

Also, Temperley's algorithm cannot deal with situations in which two or more notes with the same pitch begin at the same time. Thus, wherever two or more notes with the same pitch p began simultaneously at time t , all notes with pitch p and onset time t were removed from the *OPND* file except the one with the longest duration. This resulted in a test corpus containing 41544 notes.⁴

The "piano-roll" or MIDI-like input representations accepted by the algorithms com-

¹*OPND* stands for "onset, pitch-name, duration".

²The voice of each note is also given in the files used in the comparison, but this voice information is not used by any of the algorithms.

³Available online at <http://www.musedata.org/encodings/bach/bg/keybd/>.

⁴The complete test corpus is available online at <http://www.titanmusic.com/data.html>.

pared in this study were derived automatically from the *OPND* representations of the pieces in the test corpus.

Longuet-Higgins's algorithm Pitch spelling is one of the tasks performed by Longuet-Higgins's (1976, 1987, 1993) *music.p* program. Longuet-Higgins has published the full POP-11 source code of this program (Longuet-Higgins, 1987, pp. 120–126; Longuet-Higgins, 1993, pp. 486–492). Because of my lack of familiarity with POP-11, I decided to translate just the pitch spelling portion of *music.p* directly into Lisp in order to make it easier to perform the comparison. This was possible because the pitch spelling portion of *music.p* operates independently of the rhythmic part.⁵

The input to *music.p* must be in the form of a list of triples, $\langle p, t_{\text{on}}, t_{\text{off}} \rangle$, each triple giving the “keyboard position” p together with the onset time t_{on} and the offset time t_{off} in centiseconds of each note. The keyboard position p is simply an integer indicating the key that would have to be pressed on a normal piano keyboard in order to perform the note, with C \flat 3 mapping onto 0, C \sharp 3 and D \flat 3 mapping onto 1, C \flat 4 mapping onto 12 and so on (i.e., $p = \text{MIDI NOTE NUMBER} - 48$).

The algorithm then computes a value of “sharpness” q for each note in the input (Longuet-Higgins, 1987, p. 111). The sharpness of a pitch name indicates the position of the pitch name on the line of fifths (Temperley, 2001, p. 117) and is therefore essentially the same as Temperley's (2001, p. 118) concept of “tonal pitch class”. In Longuet-Higgins's algorithm, if q_1 and q_2 are the sharpnesses of two notes then the interval between the notes is defined to have “degree” $\delta q = q_2 - q_1$. If $|\delta q| < 6$, the interval is defined to be “diatonic”; if $|\delta q| > 6$, it is defined to be “chromatic”; and if $|\delta q| = 6$, it is defined to be “diabolic” (Longuet-Higgins, 1987, p. 112). Longuet-Higgins's algorithm attempts to spell notes so that the degree between each note and the tonic at the point at which the note occurs is not chromatic (Longuet-Higgins, 1987, p. 113). The algorithm also incorporates various rules for dealing with chromatic passages (Longuet-Higgins, 1987, pp. 113–114).

⁵My Lisp implementation of the pitch spelling portion of *music.p* is available online at <http://www.titanmusic.com/software.html>.

Pitch spelling algorithms sometimes spell complete pieces in a different key from that in which they are notated in the original score. For example, Longuet-Higgins's algorithm spells the Prelude in G \sharp minor from Book 1 of *Das Wohltemperirte Klavier* (BWV 863) in A \flat minor. I do not believe this should be considered an error. What matters is whether or not the pitch *interval* names (e.g., 'rising major third', 'falling augmented fourth', etc.) between corresponding pairs of notes are the same in the computed spelling as they are in the published score. My implementation of Longuet-Higgins's algorithm therefore actually generates three alternative spellings for each piece: 1. the spelling S for the whole input passage computed by the algorithm; 2. the spelling that results when S is transposed by a rising diminished second; and 3. the spelling that results when S is transposed by a falling diminished second. Each of these three computed spellings is then compared with the pitch names in the original score and the number of errors made by the program is taken to be the number of errors in the best of the three alternative spellings.

When my implementation of Longuet-Higgins's algorithm was run on the test corpus described above, it made only 265 errors—that is, it predicted the correct pitch name for 99.36% of the notes.

Cambouropoulos's algorithm Unlike Longuet-Higgins, Cambouropoulos has not published an implementation of his pitch spelling algorithm, nor was he able to provide me with his own implementation when I requested it. I therefore implemented my own version of his method, based on his published descriptions of it (Cambouropoulos, 1996, 1998, 2000, 2001, 2002).⁶

Cambouropoulos's method involves first converting the input representation into a sequence of *chromas* or *pitch classes* in which the chromas are in the order in which they occur in the music (the chromas of notes that occur simultaneously being ordered arbitrarily). The chroma of a note can be computed from its MIDI note number using

⁶The Lisp code for my implementation of Cambouropoulos's pitch spelling algorithm is available online at <http://www.titanmusic.com/software.html>.

the formula

$$\text{CHROMA} = \text{MIDI NOTE NUMBER} \bmod 12.$$

The term *chroma* has been used in this sense since around 1950 (Bachem, 1950; Burns and Ward, 1982, pp. 246, 262–264; Cross *et al.*, 1991, pp. 212, 223–224; Deutsch, 1982, p. 272; Deutsch, 1999, p. 350; Shepard, 1964; Shepard, 1965; Shepard, 1982, p. 352; Dowling, 1991, p. 35; Ward and Burns, 1982, p. 432–433). The term *chroma* is essentially synonymous with the term *pitch class* as used in atonal theory (Babbitt, 1960; Babbitt, 1965; Forte, 1973; Morris, 1987; Rahn, 1980).

Having derived an ordered set of chromas from the input, Cambouropoulos's algorithm then processes the music a window at a time, each window containing a fixed number of notes (set to a value between 9 and 15). Each window is positioned so that the first third of the window overlaps the last third of the previous window. Cambouropoulos allows 'white note' chromas (i.e., 0, 2, 4, 5, 7, 9 and 11) to be spelt in three different ways (e.g., chroma 0 can be spelt as B \sharp , C \flat or D $\flat\flat$) and 'black note' chromas to be spelt in two different ways (e.g., chroma 6 can be spelt as F \sharp or G \flat). Given these restricted sets of possible pitch names for each chroma, the algorithm computes all possible spellings for each window. A penalty score is then computed for each of these possible window spellings. The penalty score for a given window spelling is found by computing a penalty value for the interval between each pair of notes in the window and summing these penalty values. A given interval in a particular window spelling is penalised more heavily if it is an interval that occurs less frequently in the major and minor scales. An interval is also penalised if either of the pitch names forming the interval is a double-sharp or a double-flat. For each window, the algorithm chooses the spelling that has the lowest penalty score.

When I ran my implementation of Cambouropoulos's method on the test corpus, it made 2599 mistakes—that is, it predicted the correct pitch name for only 93.74% of the notes. When Cambouropoulos ran his own implementation of his method on the test

corpus, he found that it made even more errors than my implementation. This may be due to the fact that my implementation generates three alternative transpositions of the computed spelling and chooses the one that results in the least number of errors.

Temperley's algorithm Temperley's (1997, 2001) pitch spelling algorithm is implemented in his *harmony* program which forms one component of his and Sleator's *Melisma* system.⁷ The input to the *harmony* program must be in the form of a "note-list" (Temperley, 2001, pp. 9–12) giving the MIDI note number of each note together with its onset time and duration in milliseconds. The *harmony* program also requires a specification of the metrical structure of the input passage which can be generated by first running the note-list through Temperley and Sleator's *meter* program (another component of the *Melisma* system).

Temperley's (2001, pp. 115–136) pitch spelling algorithm searches for the spelling that best satisfies three "preference rules". The first of these rules stipulates that the algorithm should "prefer to label nearby events so that they are close together on the line of fifths" (Temperley, 2001, p. 125). This rule bears some resemblance to the basic principle underlying Longuet-Higgins's algorithm (see above). The second rule expresses the principle that if two tones are separated by a semitone and the first tone is distant from the key centre, then the interval between them should preferably be spelt as a diatonic semitone rather than a chromatic one (Temperley, 2001, p. 129). The third preference rule underlying Temperley's algorithm steers the algorithm towards spelling the notes so that a "good harmonic representation" results (Temperley, 2001, p. 131), a "good harmonic representation" being one that allows Temperley's *harmony* program to generate a correct harmonic analysis of the passage.

Because the output of the *harmony* program depends on tempo, each *OPND* representation in the test corpus had to be supplemented with a file giving a tempo map for the piece represented. These two files were then automatically converted into a note-list

⁷The complete *Melisma* system together with documentation is available online at <http://www.link.cs.cmu.edu/music-analysis/>.

in the form required by Temperley's programs. The output of the *harmony* program was then automatically converted into a format which would allow automatic comparison with the test corpus files. Again, for each piece in the test corpus, three transpositions of the spelling generated by Temperley's program were compared with the original spelling and the one with the least number of errors was selected. When Temperley's harmony program was run on the test corpus, it made only 122 mistakes—that is, it predicted the correct pitch name for 99.71% of the notes.

Summary of the invention

The invention described here consists of an algorithmic method called *ps13* that reliably computes the correct pitch names (e.g., C#4, Bb5 etc.) of the notes in a passage of tonal music, when given only the onset-time and MIDI note number of each note in the passage.

The *ps13* algorithm has been shown to be more robust than previous algorithms, correctly predicting the pitch names of 99.81% of the notes in a test corpus containing 41544 notes and consisting of all the pieces in the first book of J. S. Bach's *Das Wohltemperirte Klavier* (i.e., *ps13* incorrectly predicted the pitch names of only 81 notes in this test corpus).

Three previous algorithms (those of Cambouropoulos (1996, 1998, 2000, 2001, 2002), Longuet-Higgins (1976, 1987, 1993) and Temperley (1997, 2001)) were run on the same corpus of 41544 notes. On this corpus, Cambouropoulos's algorithm made 2599 mistakes, Longuet-Higgins's algorithm made 265 mistakes and Temperley's algorithm made 122 mistakes. As *ps13* made only 81 mistakes on the same corpus, this provides evidence in support of the claim that *ps13* is more robust than previous algorithms that attempt to perform the same task.

The *ps13* algorithm is best understood to be in two parts, Part I and Part II. Part I consists of the following steps:

1. computing for each pitch class $0 \leq c \leq 11$ and each note n in the input, a pitch

letter name $S(c, n) \in \{A, B, C, D, E, F, G\}$, calculated on the assumption that c is the tonic at the point in the piece where n occurs;

2. computing for each note n in the input and each pitch class $0 \leq c \leq 11$ a value $CNT(c, n)$ giving the number of times that c occurs within a context surrounding n that includes n , some specified number K_{pre} of notes immediately preceding n and some specified number K_{post} of notes immediately following n ;
3. computing for each note n and each letter name l , the set of chromas $C(n, l) = \{c \mid S(c, n) = l\}$;
4. computing $N(l, n) = \sum_{c \in C(n, l)} CNT(c, n)$ for each note n and each pitch letter name l ;
5. computing for each note n , the letter name l for which $N(l, n)$ is a maximum.

Part II of the algorithm corrects those instances in the output of Part I where a neighbour note or passing note is erroneously predicted to have the same letter name as either the note preceding it or the note following it. Part II of *ps13*

1. lowers the letter name of every lower neighbour note for which the letter name predicted by Part I is the same as that of the preceding note;
2. raises the letter name of every upper neighbour note for which the letter name predicted by Part I is the same as that of the preceding note;
3. lowers the letter name of every descending passing note for which the letter name predicted by Part I is the same as that of the preceding note;
4. raises the letter name of every descending passing note for which the letter name predicted by Part I is the same as that of the following note;
5. lowers the letter name of every ascending passing note for which the letter name predicted by Part I is the same as that of the following note;

6. raises the letter name of every ascending passing note for which the letter name predicted by Part I is the same as that of the preceding note.

List of figures

Figure 1 Examples of notes with identical MIDI note numbers being spelt differently in different tonal contexts (from Piston, 1978, p. 8).

Figure 2 Should the Ebs be spelt as D#s? (From Piston, 1978, p. 390.)

Figure 3 (a) Bars 1 to 4 of Bach's Fugue in D minor from Book 1 of *Das Wohltemperirte Klavier* (BWV 851). (b) The *OPND* representation of the score in (a).

Figure 4 Algorithm for computing the spelling table S .

Figure 5 Algorithm for computing the relative morph list R .

Figure 6 Algorithm for computing the chord list H .

Figure 7 Neighbour note and passing note errors corrected by *ps13*.

Figure 8 Algorithm for correcting neighbour note errors.

Figure 9 Algorithm for correcting descending passing note errors.

Figure 10 Algorithm for correcting ascending passing note errors.

Figure 11 Algorithm for computing M' .

Figure 12 Algorithm for computing P .

Figure 13 *PPN* algorithm.

Detailed description of preferred implementations

The invention consists of an algorithm, called *ps13*, that takes as input a representation of a musical passage (or work or set of works) in the form of a set I of triples $\langle t, p_c, d \rangle$, each of these triples giving the onset time t , the *chromatic pitch* p_c and the duration d of a single note or sequence of tied notes. The chromatic pitch of a note is an integer indicating the interval in semitones from A₄0 to the pitch of the note (i.e., $p_c = \text{MIDI NOTE NUMBER} - 21$). The set I may be trivially derived from a MIDI file representation of the musical passage.

If $e_i = \langle t_i, p_{c,i}, d_i \rangle$ and $e_j = \langle t_j, p_{c,j}, d_j \rangle$ and $e_i, e_j \in I$ then e_i is defined to be *less than* e_j , denoted by $e_i < e_j$, if and only if $t_i < t_j$ or $(t_i = t_j \wedge p_{c,i} < p_{c,j})$ or $(t_i = t_j \wedge p_{c,i} = p_{c,j} \wedge d_i < d_j)$. Also, $e_i \leq e_j$ if and only if $e_i < e_j$ or $e_i = e_j$.

The first step in *ps13* is to sort the set I to give an ordered set

$$J = \langle \langle t_1, p_{c,1}, d_1 \rangle, \langle t_2, p_{c,2}, d_2 \rangle, \dots, \langle t_{|I|}, p_{c,|I|}, d_{|I|} \rangle \rangle \quad (1)$$

containing all and only the elements of I , sorted into increasing order so that $j > i \Rightarrow \langle t_i, p_{c,i}, d_i \rangle \leq \langle t_j, p_{c,j}, d_j \rangle$ for all $\langle t_i, p_{c,i}, d_i \rangle, \langle t_j, p_{c,j}, d_j \rangle \in J$.

The second step in *ps13* is to compute the ordered set

$$C = \langle c_1, c_2, \dots, c_k, \dots, c_{|J|} \rangle \quad (2)$$

where $c_k = p_{c,k} \bmod 12$, $p_{c,k}$ being the chromatic pitch of the k th element of J . c_k is the *chroma* of $p_{c,k}$.

If A is an ordered set of elements,

$$A = \langle a_1, a_2, \dots, a_k, \dots, a_{|A|} \rangle$$

then let $A[j]$ denote the $(j + 1)$ th element of A (e.g., $A[0] = a_1, A[1] = a_2$). Also, let

$A[j, k]$ denote the ordered set that contains all the elements of A from $A[j]$ to $A[k - 1]$, inclusive (e.g., $A[1, 4] = \langle a_2, a_3, a_4 \rangle$).

In addition to the set I , *ps13* takes as input two numerical parameters, which I call the *precontext*, denoted by K_{pre} , and the *postcontext*, denoted by K_{post} . The precontext must be an integer greater than or equal to 0 and the postcontext must be an integer greater than 0. The third step in *ps13* is to compute the ordered set

$$\Phi = \langle \phi(C[0]), \phi(C[1]), \dots, \phi(C[k]), \dots, \phi(C[|C| - 1]) \rangle \quad (3)$$

where

$$\phi(C[k]) = \langle \text{CNT}(0, k), \text{CNT}(1, k), \dots, \text{CNT}(11, k) \rangle \quad (4)$$

and $\text{CNT}(c, k)$ returns the number of times that the chroma c occurs in the ordered set $C[\max(\{0, k - K_{\text{pre}}\}), \min(\{|C|, k + K_{\text{post}}\})]$ (the functions $\max(B)$ and $\min(B)$ return the greatest and least values, respectively, in the set B).

Every pitch name has three parts: a *letter name* which must be a member of the set $\{A, B, C, D, E, F, G\}$; an *inflection* which must be a member of the infinite set $\{\dots, \times\times, \sharp\times, \times, \sharp, \flat, b, bb, bbb, bbbb, \dots\}$; and an *octave number* which must be an integer. By convention, if the inflection of a pitch name is equal to \flat it may be omitted, for example, $C\flat 4$ may be written $C4$. The octave number of ‘middle C’ is 4 and the octave number of any other C is one greater than the next C below it *on the staff* and one less than the next C above it *on the staff*. The octave number of any pitch name whose letter name is not C is the same as that of the nearest C below it *on the staff*. Thus $B\times 3$ sounds one semitone higher than $C4$ and $Cb4$ has the same sounding pitch as $B\sharp 3$.

If N is a pitch name with letter name $l(N)$ and octave number $o(N)$, then the *morph* of N , denoted by $m(N)$, is given by the following table

$l(N)$	A	B	C	D	E	F	G
$m(N)$	0	1	2	3	4	5	6

The *morphetic octave* of N , denoted by $o_m(N)$, is given by

$$o_m(N) = \begin{cases} o(N), & \text{if } m = 0 \text{ or } m = 1, \\ o(N) - 1, & \text{otherwise.} \end{cases} \quad (5)$$

The *morphetic pitch* of N , denoted by $p_m(N)$, is given by

$$p_m(N) = m(N) + 7o_m(N). \quad (6)$$

The fourth step in *ps13* is to compute what I call the *spelling table*, S . This is done using the algorithm expressed in pseudo-code in Figure 4. In this pseudo-code, block structure is indicated by indentation and the symbol “ \leftarrow ” is used to denote assignment of a value to a variable (i.e., the expression “ $x \leftarrow y$ ” means “the value of variable x becomes equal to the value of y ”). The symbol “ \oplus ” is used to denote concatenation of ordered sets. Thus, if A and B are two ordered sets such that $A = \langle a_1, a_2, \dots, a_{|A|} \rangle$ and $B = \langle b_1, b_2, \dots, b_{|B|} \rangle$, then

$$A \oplus B = \langle a_1, a_2, \dots, a_{|A|}, b_1, b_2, \dots, b_{|B|} \rangle.$$

Also, $A \oplus \langle \rangle = \langle \rangle \oplus A = A$.

Having computed the spelling table S , the algorithm goes on to compute what I call the *relative morph list*, R . This is computed using the algorithm in Figure 5. If A is an ordered set of ordered sets, then $A[i][j]$ denotes the $(j + 1)$ th element of the $(i + 1)$ th element of A . The expression $S[k][i]$ in line 6 of Figure 5 therefore denotes the $(i + 1)$ th element of the $(k + 1)$ th element of the spelling table S . If L is an ordered set and i is the value of at least one element of L , then the function $POS(i, L)$ called in line 10 of Figure 5 returns the least value of k for which $L[k] = i$.

The next step in *ps13* is to compute the *initial morph* m_{init} which is given by

$$m_{\text{init}} = Q_{\text{init}}[C[0]] \quad (7)$$

where $Q_{\text{init}} = \langle 0, 1, 1, 2, 2, 3, 4, 4, 5, 5, 6, 6 \rangle$.

Next, *ps13* computes the *morph list*, M , which satisfies the following condition

$$(|M| = |C|) \wedge (M[i] = (R[i] + m_{\text{init}}) \bmod 7 \text{ for all } 0 \leq i < |C|). \quad (8)$$

Next, the ordered set O is computed which satisfies the following condition

$$(|O| = |C|) \wedge (O[i] = \langle J[i][0], C[i], M[i] \rangle \text{ for all } 0 \leq i < |C|). \quad (9)$$

Next, the ordered set H , which I call the *chord list* is computed using the algorithm in Figure 6.

In the next three steps, the algorithm ensures that neighbour note and passing note figures are spelt correctly. Figure 7 illustrates the six types of error corrected by the algorithm. Figure 7a shows a lower neighbour note figure that is incorrectly spelt because the neighbour note (the middle note) has the same morphetic pitch as the two flanking notes. In this case, the morphetic pitch of the neighbour note is one greater than it should be. Figure 7b shows a similar error in the case of an upper neighbour note figure. In this case, the morphetic pitch of the neighbour note is one less than it should be. The passing note figures in Figure 7c and d are incorrect because the morphetic pitch of the passing note (the middle note) is one greater than it should be. Finally, the passing note figures in Figure 7e and f are incorrect because the morphetic pitch of the passing note is one less than it should be.

ps13 first corrects errors like the ones in Figure 7a and b using the algorithm in Figure 8. If A is an ordered set of ordered sets then the expression $A[i][j, k]$ denotes the ordered set $\langle A[i][j], A[i][j+1], \dots, A[i][k-1] \rangle$. Thus, the expression $H[i+2][k][1, 3]$ in

line 4 of Figure 8 denotes the ordered set $\langle H[i+2][k][1], H[i+2][k][2] \rangle$. In Figure 7a and b, the neighbour note is one semitone away from the flanking notes. The algorithm in Figure 8 also corrects instances where the neighbour note is 2 semitones above or below the flanking notes but has the same morphetic pitch as the flanking notes.

Next, *ps13* corrects errors like the ones in Figure 7c and e using the algorithm in Figure 9. Then it corrects errors like the ones in Figure 7d and f using the algorithm in Figure 10. In Figure 7c, d, e and f, the interval between the flanking notes is a minor third. The algorithms in Figures 9 and 10 also correct instances where the interval between the flanking notes is a major third.

Having corrected neighbour note and passing note errors, *ps13* then computes a new morph list M' using the algorithm in Figure 11.

Having computed M' , it is now possible to compute a morphetic pitch for each note. This can be done using the algorithm in Figure 12 which computes the ordered set of morphetic pitches, P .

Finally, from J and P , *ps13* computes an *OPND* representation Z which satisfies the following condition

$$(|Z| = |J|) \wedge (Z[i] = \langle J[i][0], PPN(\langle J[i][1], P[i] \rangle), J[i][2] \rangle \text{ for all } 0 \leq i < |Z|). \quad (10)$$

The function $PPN(\langle p_c, p_m \rangle)$ returns the unique pitch name whose chromatic pitch is p_c and whose morphetic pitch is p_m . This function can be computed using the algorithm in Figure 13. In this algorithm, anything in double inverted commas (“”) is a string—that is, an ordered set of characters. If A and B are strings such that $A = “abcdef”$ and $B = “ghijkl”$, then the concatenation of A onto B , denoted by $A \oplus B$, is “abcdefghijkl”. In the pitch names generated by *PPN*, the sharp signs are represented by ‘s’ characters and the flat signs are represented by ‘f’ characters. A double sharp is represented by the string “ss”. For example, the pitch name $C\sharp 4$ is represented in *PPN* by the string “Css4”. The empty string is denoted by “” and the function $STR(n)$ called in line 23 returns a string

representation of the number n . For example, $STR(-5) = "-5"$, $STR(105.6) = "105.6"$.

Results of running *ps13* on the test corpus As explained above, *ps13* takes as input a set I of triples, $\langle t, p_c, d \rangle$, each one giving the onset time, chromatic pitch and duration of each note. In addition, *ps13* requires two numerical parameters, the precontext, K_{pre} , and the postcontext, K_{post} .

In order to determine the values of K_{pre} and K_{post} that give the best results, *ps13* was run on the test corpus 2500 times, each time using a different pair of values $\langle K_{pre}, K_{post} \rangle$ chosen from the set $\{\langle K_{pre}, K_{post} \rangle \mid 1 \leq K_{pre}, K_{post} \leq 50\}$. For each pair of values $\langle K_{pre}, K_{post} \rangle$, the number of errors made by *ps13* on the test corpus was recorded.

ps13 made fewer than 122 mistakes (i.e., performed better than Temperley's algorithm) on the test corpus for 2004 of the 2500 $\langle K_{pre}, K_{post} \rangle$ pairs tested (i.e., 80.160% of the $\langle K_{pre}, K_{post} \rangle$ pairs).

ps13 performed best on the test corpus when K_{pre} was set to 33 and K_{post} was set to either 23 or 25. With these parameter values, *ps13* made only 81 errors on the test corpus—that is, it correctly predicted the pitch names of 99.805% of the notes in the test corpus.

The mean number of errors made by *ps13* over all 2500 $\langle K_{pre}, K_{post} \rangle$ pairs was 109.082 (i.e., 99.737% of the notes were correctly spelt on average over all 2500 $\langle K_{pre}, K_{post} \rangle$ pairs). This average value is better than the result obtained by Temperley's algorithm for this test corpus.

The worst result was obtained when both K_{pre} and K_{post} were set to 1. In this case, *ps13* made 1117 errors (97.311% correct). However, provided K_{pre} is greater than about 14 and K_{post} is greater than about 21, *ps13* predicts the correct pitch name for over 99.75% of the notes in the test corpus.

A Lisp implementation of *ps13* The Lisp implementation of *ps13* given below assumes that the input representation I is represented as a list of sublists, each sublist

taking the form $(t p_c d)$ where t , p_c and d are the onset time, chromatic pitch and duration, respectively, of a single note. For example, the passage in Figure 3a would be represented by the list

```
((2 41 2) (4 43 2) (6 44 2) (8 46 2) (10 43 2) (12 44 1) (13 41 1) (14 40 1)
(15 41 1) (16 49 4) (20 46 4) (24 48 5) (26 36 2) (28 38 2) (29 46 1)
(30 39 2) (30 44 1) (31 43 1) (32 41 2) (32 46 1) (33 44 1) (34 38 2)
(34 43 1) (35 41 1) (36 39 1) (36 43 2) (37 36 1) (38 35 1) (38 51 3)
(39 36 1) (40 44 4) (41 50 1) (42 48 1) (43 50 1) (44 41 4) (44 50 1)
(45 48 1) (46 47 1) (47 48 1))
```

Similarly, the output of the Lisp implementation of *ps13* given below is represented as a list of sublists. For example, the output of this implementation of *ps13* for the passage given in Figure 3a is

```
((2 "Dn4" 2) (4 "En4" 2) (6 "Fn4" 2) (8 "Gn4" 2) (10 "En4" 2) (12 "Fn4" 1)
(13 "Dn4" 1) (14 "Cs4" 1) (15 "Dn4" 1) (16 "Bf4" 4) (20 "Gn4" 4) (24 "An4" 5)
(26 "An3" 2) (28 "Bn3" 2) (29 "Gn4" 1) (30 "Cn4" 2) (30 "Fn4" 1) (31 "En4" 1)
(32 "Dn4" 2) (32 "Gn4" 1) (33 "Fn4" 1) (34 "Bn3" 2) (34 "En4" 1) (35 "Dn4" 1)
(36 "Cn4" 1) (36 "En4" 2) (37 "An3" 1) (38 "Gs3" 1) (38 "Cn5" 3) (39 "An3" 1)
(40 "Fn4" 4) (41 "Bn4" 1) (42 "An4" 1) (43 "Bn4" 1) (44 "Dn4" 4) (44 "Bn4" 1)
(45 "An4" 1) (46 "Gs4" 1) (47 "An4" 1))
```

Here, then, is the Lisp code for an implementation of *ps13*:

```
(defun ps13 (&optional (input-filename (choose-file-dialog))
              (pre-context 33)
              (post-context 23))
  (let* ((sorted-input-representation
          (remove-duplicates
           (sort (with-open-file (input-file
                                  input-filename)
                                (read input-file))
                  #'vector-less-than)
           :test #'equalp))
         (onset-list (mapcar #'first sorted-input-representation))
         (chromatic-pitch-list
          (mapcar #'second sorted-input-representation))
         (chroma-list
          (mapcar #'chromatic-pitch-chroma chromatic-pitch-list))
         (n (list-length chroma-list))
         (chroma-vector-list
          (do* ((cvl nil)
                (i 0 (1+ i)))
```

```

      ((= i n)
        cvl)
    (setf cvl
      (append cvl
        (list
          (do* ((context
                (subseq chroma-list
                  (max 0 (- i pre-context))
                  (min n (+ i post-context))))
            (cv (list 0 0 0 0 0 0 0 0 0 0 0 0))
              (c 0 (+ 1 c)))
            ((= c 12)
              cv)
            (setf (elt cv c)
              (count c context)))))))))
  (chromamorph-table (list 0 1 1 2 2 3 3 4 5 5 6 6))
  (spelling-table
    (do* ((first-morph nil nil)
          (spelling nil nil)
          (spelling2 nil nil)
          (st nil)
          (c 0 (1+ c)))
      ((= c 12)
        st)
      (setf spelling
        (mapcar #'(lambda (chroma-in-chroma-list)
                     (elt chromamorph-table
                       (mod (- chroma-in-chroma-list c) 12)))
                  chroma-list))
        (setf first-morph (first spelling))
        (setf spelling2
          (mapcar #'(lambda (morph-in-spelling)
                      (mod (- morph-in-spelling first-morph) 7))
                  spelling))
        (setf st (append st (list spelling2)))))
  (relative-morph-list
    (do ((morph-vector (list 0 0 0 0 0 0 0)
                        (list 0 0 0 0 0 0 0))
        (rml nil)
        (i 0 (1+ i))
        (morphs-for-this-chroma nil
          nil)
        )
      ((= i n)
        rml)
      (setf morphs-for-this-chroma
        (mapcar #'(lambda (spelling)
                     (elt spelling i))
          (elt chromamorph-table
            (mod (- chroma-in-chroma-list c) 12)))))

```

```

        spelling-table))
(setf rml
  (do ((prev-score nil nil)
        (j 0 (1+ j)))
      ((= j 12)
       ;(pprint morph-vector)
       (append rml
                (list (position
                       (apply #'max morph-vector)
                       morph-vector)))))
  (setf prev-score
        (elt morph-vector
              (elt morphs-for-this-chroma j)))
  (setf (elt morph-vector
            (elt morphs-for-this-chroma j))
        (+ prev-score
            (elt (elt chroma-vector-list i) j))))))
(initial-morph (elt '(0 1 1 2 2 3 4 4 5 6 6)
                    (mod (first chromatic-pitch-list) 12)))
(morph-list (mapcar #'(lambda (relative-morph)
                        (mod (+ relative-morph initial-morph) 7))
                  relative-morph-list))
(ocm (mapcar #'list onset-list chroma-list morph-list))
(ocm-chord-list (do* ((cl (list (list (first ocm))))
                     (i 1 (1+ i)))
                     ((= i n)
                      cl)
                     (if (= (first (elt ocm i))
                            (first (elt ocm (1- i))))
                         (setf (first (last cl))
                               (append (first (last cl))
                                         (list (elt ocm i))))
                         (setf cl
                               (append cl
                                         (list (list (elt ocm i)))))))
  (list (list (elt ocm i))))))
(number-of-chords (list-length ocm-chord-list))
;neighbour notes
(ocm-chord-list
 (do* ((i 0 (1+ i)))
      ((= i (- number-of-chords 2))
       ocm-chord-list)
      (dolist (note1 (elt ocm-chord-list i))
        (if (member (cdr note1)
                     (mapcar #'cdr (elt ocm-chord-list (+ i 2)))
                     :test #'equalp)
            (dolist (note2 (elt ocm-chord-list (1+ i)))
              (if (= (third note2)
                     (third note1))

```

```

(progn
  (if (member (mod (- (second note2) (second note1))
                    12)
          '(1 2))
      (setf (third note2)
            (mod (+ 1 (third note2)) 7)))
  (if (member (mod (- (second note1) (second note2))
                    12)
          '(1 2))
      (setf (third note2)
            (mod (- (third note2) 1) 7)))))))))
;downward passing notes
(ocm-chord-list
 (do* ((i 0 (1+ i)))
      ((= i (- number-of-chords 2))
       ocm-chord-list)
  (dolist (note1 (elt ocm-chord-list i))
    (dolist (note3 (elt ocm-chord-list (+ i 2)))
      (if (= (third note3) (mod (- (third note1) 2) 7))
          (dolist (note2 (elt ocm-chord-list (1+ i)))
            (if (and (or (= (third note2)
                           (third note1))
                       (= (third note2)
                           (third note3)))
                (< 0
                 (mod (- (second note1) (second note2))
                       12)
                 (mod (- (second note1) (second note3))
                       12))))
            (unless (remove-if
                     #'null
                     (mapcar
                      #'(lambda (note)
                        (/= (second note)
                            (second note2)))
                      (remove-if
                       #'null
                       (mapcar
                        #'(lambda (note)
                          (if (= (third note)
                                (mod (- (third note1) 1)
                                      7))
                              note))
                        (elt ocm-chord-list (1+ i)))))))
              (setf (third note2)
                    (mod (- (third note1) 1) 7)))))))))
;upward passing notes
(ocm-chord-list

```

```

(do* ((i 0 (1+ i)))
  ((= i (- number-of-chords 2))
    ocm-chord-list)
  (dolist (note1 (elt ocm-chord-list i))
    (dolist (note3 (elt ocm-chord-list (+ i 2)))
      (if (= (third note3) (mod (+ (third note1) 2) 7))
        (dolist (note2 (elt ocm-chord-list (1+ i)))
          (if (and (or (= (third note2)
                        (third note1))
                    (= (third note2)
                        (third note3)))
              (< 0
                (mod (- (second note3) (second note2))
                      12)
                (mod (- (second note3) (second note1))
                      12))))
            (unless (remove-if
                     #'null
                     (mapcar
                      #'(lambda (note)
                        (/= (second note)
                            (second note2)))
                      (remove-if
                       #'null
                       (mapcar #'(lambda (note)
                                  (if (= (third note)
                                         (mod (+ (third note1)
                                                1)
                                                7))
                                      note))
                               (elt ocm-chord-list (1+ i)))))))
              (setf (third note2)
                    (mod (+ (third note1) 1) 7)))))))))
(morph-list (mapcar #'third (apply #'append ocm-chord-list)))
(morphetic-pitch-list
 (mapcar #'(lambda (chromatic-pitch morph)
   (let* ((morphetic-octave1 (floor chromatic-pitch 12))
          (morphetic-octave2 (+ 1 morphetic-octave1))
          (morphetic-octave3 (- morphetic-octave1 1))
          (mp1 (+ morphetic-octave1 (/ morph 7)))
          (mp2 (+ morphetic-octave2 (/ morph 7)))
          (mp3 (+ morphetic-octave3 (/ morph 7)))
          (chroma (mod chromatic-pitch 12))
          (cp (+ morphetic-octave1 (/ chroma 12)))
          (difference-list (list (abs (- cp mp1))
                                  (abs (- cp mp2))
                                  (abs (- cp mp3))))
          (morphetic-octave-list (list morphetic-octave1

```

```

morphic-octave2
morphic-octave3))

(best-morphic-octave
  (elt morphic-octave-list
    (position (apply #'min difference-list)
              difference-list))))
(+ (* 7 best-morphic-octave) morph))
chromatic-pitch-list
morph-list))
(opnd (mapcar #'(lambda (tpcd-triple morphic-pitch)
  (list (first tpcd-triple)
        (list (second tpcd-triple)
              morphic-pitch)
        (third tpcd-triple)))
  sorted-input-representation
  morphic-pitch-list))
(opnd (mapcar #'(lambda (opnd-datapoint)
  (list (first opnd-datapoint)
        (p-pn (second opnd-datapoint))
        (third opnd-datapoint)))
  opnd)))
opnd))

(defun chromatic-pitch-chroma (chromatic-pitch)
  (mod chromatic-pitch 12))

(defun vector-less-than (v1 v2)
  (cond ((null v2) nil)
        ((null v1) t)
        ((< (first v1) (first v2)) t)
        ((> (first v1) (first v2)) nil)
        (t (vector-less-than (cdr v1) (cdr v2)))))

(defun p-pn (p)
  (let* ((m (p-m p))
         (l (elt '("A" "B" "C" "D" "E" "F" "G") m))
         (gc (p-gc p))
         (cdash (elt '(0 2 3 5 7 8 10) m))
         (e (- gc cdash))
         (i ""))
    (i (cond ((< e 0)
              (dotimes (j (- e) i)
                (setf i (concatenate 'string i "f")))))
      ((> e 0)
       (dotimes (j e i)
         (setf i (concatenate 'string i "s"))))
      ((= e 0) "n")))
  (om (p-om p))

```

```

(oasa (if (or (= m 0) (= m 1))
          om
          (+ 1 om)))
(o (format nil "~D" oasa)))
(concatenate 'string l i o)))

(defun p-om (p)
  (div (p-pm p) 7))

(defun p-pm (p)
  (second p))

(defun div (x y)
  (int (/ x y)))

(defun int (x)
  (values (floor x)))

(defun p-gc (p)
  (- (p-pc p)
     (* 12 (p-om p))))

(defun p-pc (p)
  (first p))

(defun p-m (p)
  (bmod (p-pm p) 7))

(defun bmod (x y)
  (- x
     (* y
        (int (/ x y)))))

```

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CLAIMS

1. A method for computing the pitch names (i.e., C \sharp 4, Bb3, etc.) of notes in a representation of music in which at least the onset time and MIDI note number (or chromatic pitch) of each note is given, comprising the steps of
 - (a) computing for each pitch class $0 \leq c \leq 11$ and each note n in the input, a pitch letter name $S(c, n) \in \{A, B, C, D, E, F, G\}$, calculated on the assumption that c is the tonic at the point in the piece where n occurs;
 - (b) computing for each note n in the input and each pitch class $0 \leq c \leq 11$ a value $CNT(c, n)$ giving the number of times that c occurs within a context surrounding n that includes n , some specified number K_{pre} of notes immediately preceding n and some specified number K_{post} of notes immediately following n ;
 - (c) computing for each note n and each letter name l , the set of chromas $C(n, l) = \{c \mid S(c, n) = l\}$;
 - (d) computing $N(l, n) = \sum_{c \in C(n, l)} CNT(c, n)$ for each note n and each pitch letter name l ;
 - (e) computing for each note n , the letter name l for which $N(l, n)$ is a maximum.
2. The method of Claim 1, adapted to correct those errors in the output of the method of Claim 1 in which a neighbour note or passing note is erroneously predicted to have the same letter name as either the note preceding it or the note following it, comprising the further steps of
 - (a) lowering the letter name of every lower neighbour note for which the letter name predicted by the method of Claim 1 is the same as that of the preceding note;
 - (b) raising the letter name of every upper neighbour note for which the letter name predicted by the method of Claim 1 is the same as that of the preceding note;

- (c) lowering the letter name of every descending passing note for which the letter name predicted by the method of Claim 1 is the same as that of the preceding note;
 - (d) raising the letter name of every descending passing note for which the letter name predicted by the method of Claim 1 is the same as that of the following note;
 - (e) lowering the letter name of every ascending passing note for which the letter name predicted by the method of Claim 1 is the same as that of the following note;
 - (f) raising the letter name of every ascending passing note for which the letter name predicted by the method of Claim 1 is the same as that of the preceding note.
3. Computer software or hardware adapted for performing the method of any preceding Claim 1-2.

ABSTRACT

METHOD OF COMPUTING THE PITCH NAMES OF NOTES IN MIDI-LIKE MUSIC REPRESENTATIONS

The invention described here consists of an algorithmic method called *ps13* that reliably computes the correct pitch names (e.g., C#4, Bb5 etc.) of the notes in a passage of tonal music, when given only the onset-time and MIDI note number of each note in the passage.

The *ps13* algorithm has been shown to be more robust than previous algorithms, correctly predicting the pitch names of 99.81% of the notes in a test corpus containing 41544 notes and consisting of all the pieces in the first book of J. S. Bach's *Das Wohltemperirte Klavier* (i.e., *ps13* incorrectly predicted the pitch names of only 81 notes in this test corpus).

Three previous algorithms (those of Cambouropoulos (1996, 1998, 2000, 2001, 2002), Longuet-Higgins (1976, 1987, 1993) and Temperley (1997, 2001)) were run on the same corpus of 41544 notes. On this corpus, Cambouropoulos's algorithm made 2599 mistakes, Longuet-Higgins's algorithm made 265 mistakes and Temperley's algorithm made 122 mistakes. As *ps13* made only 81 mistakes on the same corpus, this provides evidence in support of the claim that *ps13* is more robust than previous algorithms that attempt to perform the same task.

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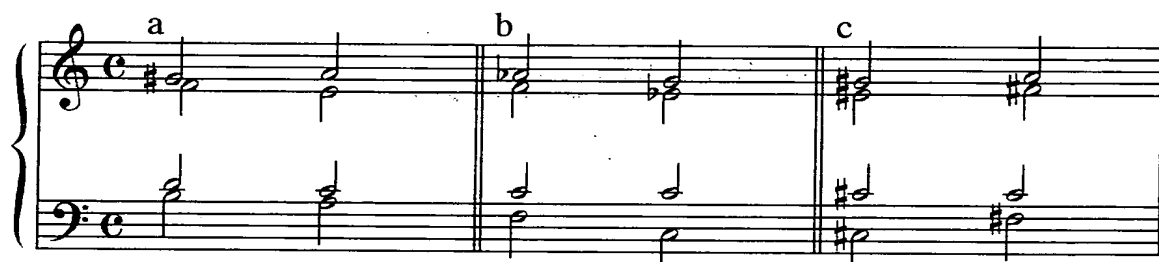


Figure 1: Examples of notes with identical MIDI note numbers being spelt differently in different tonal contexts (from Piston, 1978, p. 8).

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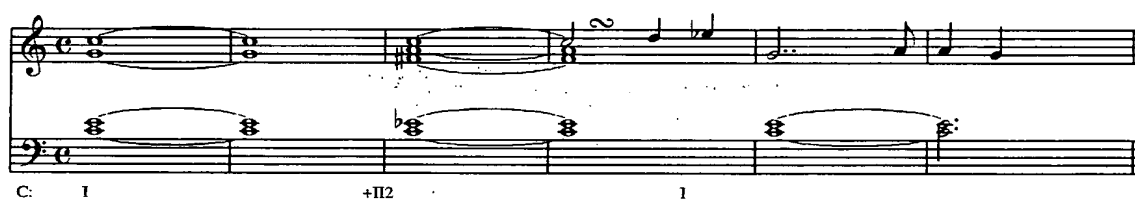



Figure 2: Should the Ebs be spelt as D#s? (From Piston, 1978, p. 390.)

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(a) 

(b) { $\langle 2 \text{ D4 } 2 \rangle$, $\langle 4 \text{ E4 } 2 \rangle$, $\langle 6 \text{ F4 } 2 \rangle$, $\langle 8 \text{ G4 } 2 \rangle$, $\langle 10 \text{ E4 } 2 \rangle$, $\langle 12 \text{ F4 } 1 \rangle$,
 $\langle 13 \text{ D4 } 1 \rangle$, $\langle 14 \text{ CS4 } 1 \rangle$, $\langle 15 \text{ D4 } 1 \rangle$, $\langle 16 \text{ BF4 } 4 \rangle$, $\langle 20 \text{ G4 } 4 \rangle$, $\langle 24 \text{ A4 } 5 \rangle$,
 $\langle 29 \text{ G4 } 1 \rangle$, $\langle 30 \text{ F4 } 1 \rangle$, $\langle 31 \text{ E4 } 1 \rangle$, $\langle 32 \text{ G4 } 1 \rangle$, $\langle 33 \text{ F4 } 1 \rangle$, $\langle 34 \text{ E4 } 1 \rangle$,
 $\langle 35 \text{ D4 } 1 \rangle$, $\langle 36 \text{ E4 } 2 \rangle$, $\langle 38 \text{ C5 } 3 \rangle$, $\langle 41 \text{ B4 } 1 \rangle$, $\langle 42 \text{ A4 } 1 \rangle$, $\langle 43 \text{ B4 } 1 \rangle$,
 $\langle 44 \text{ B4 } 1 \rangle$, $\langle 45 \text{ A4 } 1 \rangle$, $\langle 46 \text{ GS4 } 1 \rangle$, $\langle 47 \text{ A4 } 1 \rangle$, $\langle 26 \text{ A3 } 2 \rangle$, $\langle 28 \text{ B3 } 2 \rangle$,
 $\langle 30 \text{ C4 } 2 \rangle$, $\langle 32 \text{ D4 } 2 \rangle$, $\langle 34 \text{ B3 } 2 \rangle$, $\langle 36 \text{ C4 } 1 \rangle$, $\langle 37 \text{ A3 } 1 \rangle$, $\langle 38 \text{ GS3 } 1 \rangle$,
 $\langle 39 \text{ A3 } 1 \rangle$, $\langle 40 \text{ F4 } 4 \rangle$, $\langle 44 \text{ D4 } 4 \rangle$ }

Figure 3: (a) Bars 1 to 4 of Bach's Fugue in D minor from Book 1 of *Das Wohltemperirte Klavier* (BWV 851). (b) The *OPND* representation of the score in (a).

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```

1   $S \leftarrow \langle \rangle$ 
2   $Q \leftarrow \langle 0, 1, 1, 2, 2, 3, 3, 4, 5, 5, 6, 6 \rangle$ 
3  for  $c \leftarrow 0$  to 11
4       $m_0 \leftarrow 0$ 
5       $s \leftarrow \langle \rangle$ 
6       $s' \leftarrow \langle \rangle$ 
7      for  $i \leftarrow 0$  to  $|C| - 1$ 
8           $s \leftarrow s \oplus \langle Q[(C[i] - c) \bmod 12] \rangle$ 
9           $m_0 \leftarrow s[0]$ 
10     for  $i \leftarrow 0$  to  $|C| - 1$ 
11          $s' \leftarrow s' \oplus \langle (s[i] - m_0) \bmod 7 \rangle$ 
12      $S \leftarrow S \oplus \langle s' \rangle$ 
13 return  $S$ 

```

Figure 4: Algorithm for computing the spelling table S .

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```

1   $R \leftarrow \langle \rangle$ 
2  for  $i \leftarrow 0$  to  $|C| - 1$ 
3       $V \leftarrow \langle 0, 0, 0, 0, 0, 0, 0 \rangle$ 
4       $\mu \leftarrow \langle \rangle$ 
5      for  $k \leftarrow 0$  to 11
6           $\mu \leftarrow \mu \oplus \langle S[k][i] \rangle$ 
7      for  $j \leftarrow 0$  to 11
8           $s_{\text{prev}} \leftarrow V[\mu[j]]$ 
9           $V[\mu[j]] \leftarrow s_{\text{prev}} + \Phi[i][j]$ 
10      $R \leftarrow R \oplus \langle POS(\max(V), V) \rangle$ 
11 return  $R$ 

```

Figure 5: Algorithm for computing the relative morph list R .

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1   $H \leftarrow \langle \langle O[0] \rangle \rangle$ 
2  for  $i \leftarrow 1$  to  $|C| - 1$ 
3      if  $O[i][0] = O[i-1][0]$ 
4           $H[|H| - 1] \leftarrow H[|H| - 1] \oplus \langle O[i] \rangle$ 
5      else
6           $H \leftarrow H \oplus \langle \langle O[i] \rangle \rangle$ 
7  return  $H$ 

```

Figure 6: Algorithm for computing the chord list H .

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Figure 7: Neighbour note and passing note errors corrected by *ps13*.

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1  for  $i \leftarrow 0$  to  $|H| - 3$ 
2     $\zeta \leftarrow \langle \rangle$ 
3    for  $k \leftarrow 0$  to  $|H[i+2]| - 1$ 
4       $\zeta \leftarrow \zeta \oplus \langle H[i+2][k][1,3] \rangle$ 
5    for  $n_1 \leftarrow 0$  to  $|H[i]| - 1$ 
6      if  $H[i][n_1][1,3] \in \zeta$ 
7        for  $n_2 \leftarrow 0$  to  $|H[i+1]| - 1$ 
8          if  $H[i+1][n_2][2] = H[i][n_1][2]$ 
9            if  $(H[i+1][n_2][1] - H[i][n_1][1]) \bmod 12 \in \{1, 2\}$ 
10              $H[i+1][n_2][2] \leftarrow (H[i+1][n_2][2] + 1) \bmod 7$ 
11            if  $(H[i][n_1][1] - H[i+1][n_2][1]) \bmod 12 \in \{1, 2\}$ 
12              $H[i+1][n_2][2] \leftarrow (H[i+1][n_2][2] - 1) \bmod 7$ 
13  return  $H$ 

```

Figure 8: Algorithm for correcting neighbour note errors.

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```

1  for  $i \leftarrow 0$  to  $|H| - 3$ 
2    for  $n_1 \leftarrow 0$  to  $|H[i]| - 1$ 
3      for  $n_3 \leftarrow 0$  to  $|H[i+2]| - 1$ 
4        if  $H[i+2][n_3][2] = (H[i][n_1][2] - 2) \bmod 7$ 
5          for  $n_2 \leftarrow 0$  to  $|H[i+1]| - 1$ 
6            if  $H[i+1][n_2][2] = H[i][n_1][2]$  or  $H[i+1][n_2][2] = H[i+2][n_3][2]$ 
7              if  $0 < (H[i][n_1][1] - H[i+1][n_2][1]) \bmod 12 < (H[i][n_1][1] - H[i+2][n_3][1]) \bmod 12$ 
8                 $\zeta \leftarrow \langle \rangle$ 
9                for  $j \leftarrow 0$  to  $|H[i+1]| - 1$ 
10                  if  $H[i+1][j][2] = (H[i][n_1][2] - 1) \bmod 7$ 
11                     $\zeta \leftarrow \zeta \oplus \langle H[i+1][j] \rangle$ 
12                   $\theta \leftarrow \langle \rangle$ 
13                  for  $j \leftarrow 0$  to  $|\zeta| - 1$ 
14                    if  $H[i+1][n_2][1] \neq \zeta[j][1]$ 
15                       $\theta \leftarrow \theta \oplus \langle \zeta[j] \rangle$ 
16                    if  $\theta = \langle \rangle$ 
17                       $H[i+1][n_2][2] \leftarrow (H[i][n_1][2] - 1) \bmod 7$ 
18 return  $H$ 

```

Figure 9: Algorithm for correcting descending passing note errors.

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```

1  for  $i \leftarrow 0$  to  $|H| - 3$ 
2    for  $n_1 \leftarrow 0$  to  $|H[i]| - 1$ 
3      for  $n_3 \leftarrow 0$  to  $|H[i+2]| - 1$ 
4        if  $H[i+2][n_3][2] = (H[i][n_1][2] + 2) \bmod 7$ 
5          for  $n_2 \leftarrow 0$  to  $|H[i+1]| - 1$ 
6            if  $H[i+1][n_2][2] = H[i][n_1][2]$  or  $H[i+1][n_2][2] = H[i+2][n_3][2]$ 
7              if  $0 < (H[i+2][n_3][1] - H[i+1][n_2][1]) \bmod 12 < (H[i+2][n_3][1] - H[i][n_1][1]) \bmod 12$ 
8                 $\zeta \leftarrow \langle \rangle$ 
9                for  $j \leftarrow 0$  to  $|H[i+1]| - 1$ 
10                  if  $H[i+1][j][2] = (H[i][n_1][2] + 1) \bmod 7$ 
11                     $\zeta \leftarrow \zeta \oplus \langle H[i+1][j] \rangle$ 
12                   $\theta \leftarrow \langle \rangle$ 
13                  for  $j \leftarrow 0$  to  $|\zeta| - 1$ 
14                    if  $H[i+1][n_2][1] \neq \zeta[j][1]$ 
15                       $\theta \leftarrow \theta \oplus \langle \zeta[j] \rangle$ 
16                  if  $\theta = \langle \rangle$ 
17                     $H[i+1][n_2][2] \leftarrow (H[i][n_1][2] + 1) \bmod 7$ 
18 return  $H$ 

```

Figure 10: Algorithm for correcting ascending passing note errors.

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```

1   $O' \leftarrow \langle \rangle$ 
2  for  $i \leftarrow 0$  to  $|H| - 1$ 
3     $O' \leftarrow O' \oplus H[i]$ 
4   $M' \leftarrow \langle \rangle$ 
5  for  $i \leftarrow 0$  to  $|O'| - 1$ 
6     $M' \leftarrow M' \oplus \langle O'[i][2] \rangle$ 
7  return  $M'$ 

```

Figure 11: Algorithm for computing M' .

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```

1   $P \leftarrow \langle \rangle$ 
2  for  $i \leftarrow 0$  to  $|J| - 1$ 
3     $o_1 \leftarrow \lfloor J[i][1]/12 \rfloor$ 
4     $o_2 \leftarrow 1 + o_1$ 
5     $o_3 \leftarrow o_1 - 1$ 
6     $p_1 \leftarrow o_1 + M'[i]/7$ 
7     $p_2 \leftarrow o_2 + M'[i]/7$ 
8     $p_3 \leftarrow o_3 + M'[i]/7$ 
9     $c \leftarrow J[i][1] \bmod 12$ 
10    $p' \leftarrow o_1 + c/12$ 
11    $D \leftarrow \langle |p' - p_1|, |p' - p_2|, |p' - p_3| \rangle$ 
12    $\omega \leftarrow \langle o_1, o_2, o_3 \rangle$ 
13    $o \leftarrow \omega[\text{POS}(\min(D), D)]$ 
14    $P \leftarrow P \oplus \langle M'[i] + 7o \rangle$ 
15 return  $P$ 

```

Figure 12: Algorithm for computing P .

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```

PPN( $p$ )
1   $m \leftarrow p[1] \bmod 7$ 
2   $L \leftarrow \langle "A", "B", "C", "D", "E", "F", "G" \rangle$ 
3   $l \leftarrow L[m]$ 
4   $g_c \leftarrow p[0] - 12(\lfloor p[1]/7 \rfloor)$ 
5   $A \leftarrow \langle 0, 2, 3, 5, 7, 8, 10 \rangle$ 
6   $c' \leftarrow A[m]$ 
7   $e \leftarrow g_c - c'$ 
8   $i \leftarrow ""$ 
9  if  $e < 0$ 
10   for  $j \leftarrow 0$  to  $-e - 1$ 
11      $i \leftarrow i \oplus "f"$ 
12 else
13   if  $e > 0$ 
14     for  $j \leftarrow 0$  to  $e - 1$ 
15        $i \leftarrow i \oplus "s"$ 
16   else
17      $i \leftarrow "r"$ 
18  $o_m \leftarrow \lfloor p[1]/7 \rfloor$ 
19 if  $m = 0$  or  $m = 1$ 
20    $o \leftarrow o_m$ 
21 else
22    $o \leftarrow 1 + o_m$ 
23  $o_{str} \leftarrow STR(o)$ 
24 return  $l \oplus i \oplus o$ 

```

Figure 13: PPN algorithm.

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